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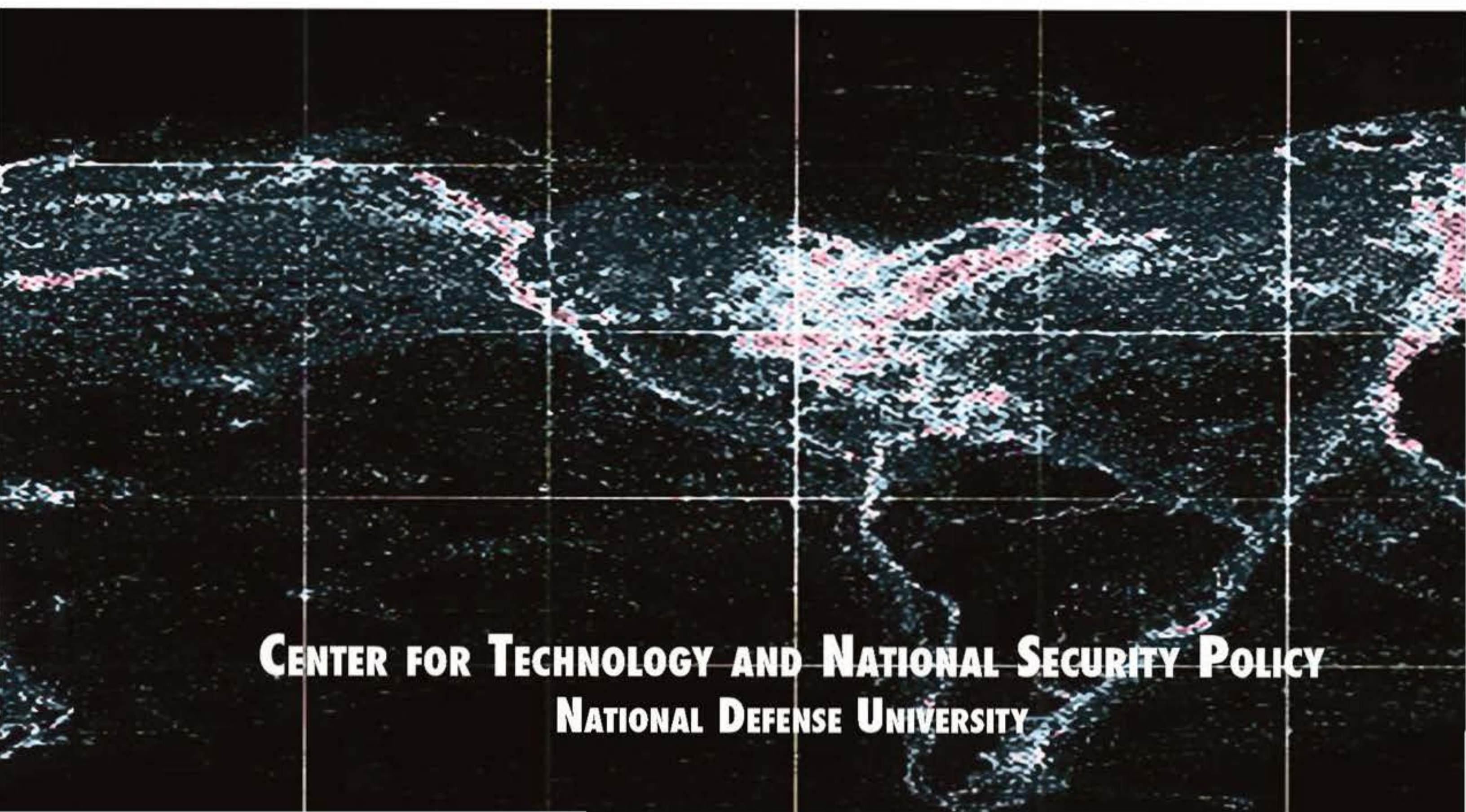
Critical Technology Events (CTEs) that Support the Rationale for Army Laboratories Based on S&T Functions Performed

James A. Ratches and John W. Lyons



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Contents

I. Introduction

Project *Hindsight*[1] was a 1969 U.S. Department of Defense (DOD) report that was an in-depth study sponsored by the Director of Defense Research & Engineering (DDR&E) and provided insights into the development of approximately 20 weapons systems across the Defense spectrum. *Hindsight* was used as a model for a series of papers, including this one, in the analysis of research projects in the DOD. Since the publication of *Hindsight*, DOD has continued to pursue research and development (R&D) and develop weapon systems to address new military threats to the United States. The Army Science & Technology (S&T) Executive sponsored a series of three reports that provided a retrospective look at the development of four major Army weapons platforms since *Hindsight*: the Abrams tank,[2] the Apache helicopter,[3] and the Stinger and Javelin[4] missiles. These three Defense & Technology Papers were focused on the Critical Technology Events (CTEs) that occurred in U.S. Army, industry, and academic laboratories that enabled these weapons platforms to have the necessary capability to accomplish their assigned missions. CTEs are ideas, concepts, models, and analyses, including key technical and managerial decisions, which have had a major impact on the development of specific weapons systems. A report that synopsizes these three platform oriented systems has been published also.[5] Additionally, another CTE-related paper has been published which diverges from the weapons platform orientation of the previous papers and focusses on Army sensor technology development.[6]

CTEs can occur at any point in the system's life cycle, from basic research, to advanced development, to testing and evaluation, to product improvements. CTEs can even relate to concepts that were developed but ultimately not incorporated into the weapons system. Also, CTEs can originate anywhere, from in-house laboratories, to private industry, to academia. CTEs are not exactly the same as the *Hindsight's* Research and Exploratory Development (RXD) Events. Unlike CTE's, RXD events have the predominant meaning of an event that "defines a scientific or engineering activity during a relatively brief time that includes the conception of a new idea and the initial demonstration of its feasibility."[7] The purpose of this paper is document that the Army laboratories, by performing the chosen CTEs in this paper, in conjunction with

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[1] Office of the Director of Defense and Engineering, *Project "Hindsight: Final Report"* (Washington, DC: Department of Defense, 1969)

[2] Richard Chait, John Lyons, and Duncan Long, *Critical Technology Events in the Development of the Abrams Tank-Project Hindsight Revisited*, Defense & Technology Paper 22 (Washington, DC: Center for Technology and National Security Policy, December 2005).

[3] Richard Chait, John Lyons, and Duncan Long, *Critical Technology Events in the Development of the Apache Helicopter-Project Hindsight Revisited*, Defense & Technology Paper 26 (Washington, DC: Center for Technology and National Security Policy, February 2006).

4. John Lyons, Duncan Long, and Richard Chait, Critical Technology events in the Development of the Stinger and Javelin Missile Systems-Project Hindsight Revisited, Defense & Technology Paper 33 (Washington, DC: Center for Technology and National Security Policy, July 2006) .

[5] John Lyons, Richard Chait, and Duncan Long, *Critical Technology Events in the Development of Selected Army Weapons Systems, A Summary of Project Hindsight Revisited*, Defense & Technology Paper 35 (Washington, DC: Center for Technology and National Security Policy, September 2006).

[6] James A. Ratches, Richard Chait, and John W. Lyons, *Some Recent Sensor-Related Army Critical Technology Events*, Defense & Technology Paper 100 (Washington, DC: Center for Technology and National Security Policy, February 2013).

[7] *Project "Hindsight: Final Report"*, xiv.

academia and industry are performing the functions identified in the 1991 report by the Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories (the Commission).[8] The referenced study was performed just prior to the 1991 Base Relocation and Closure (BRAC) findings.

Section II of this paper will begin by analyzing *Project Hindsigh*t, as well as the previous related efforts on the Abrams, Apache, and Stinger and Javelin. This present paper continues the process of documenting Army laboratory CTEs with the new purpose of relating the CTEs to the Commission's Service laboratories defined functions. By documenting Army laboratory critical technical accomplishments and associating them with the functions required of Service laboratories, the relevance, uniqueness and importance of the laboratories Research & Development (R&D) in support of and benefits to the Army's mission will be illuminated and clearly established. Section III lists the Commission's functions, and Section IV describes the CTEs for the programs selected for each function and highlighted for this paper. Section V provides a set of findings of this report, bids discussion on a variety of topics, and offers concluding remarks. It is important to understand that the CTEs chosen for discussion in this report are a subset of all the possible relevant CTEs that could be discussed and beyond those that have relevance to the Commission's functions of this paper. The present paper is associating CTEs performed by the Army S&T community in order to establish that this community is performing the technical functions that are required for any Service laboratory to perform as an indispensable, contributory member of the developmental community for Army weapon systems.

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[8] Charles E. Adolph, *Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories,* Report to the Secretary of Defense (Washington, DC: Department of Defense, September 1991), 3, available at <www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA323887>.

II. Additional Background

Project Hindsight

This study is modeled in part on a 1969 report, Project *Hindsight.* In 1965, the DOD DDR&E, Dr. Harold Brown, established a project to take a retrospective look at DOD investment in R&D, to evaluate the results, and to take stock of lessons learned. Brown's overarching objectives for the study were to identify management factors that were associated with the utilization of the results produced by the DOD S&T program and to devise a methodology to measure the return on investment. He was motivated in part by the U.S. House of Representatives Committee on Defense Appropriations, which had questioned the efficiency of management and overall payoff for the part of the Research, Development, Testing and Evaluation (RDT&E) program that pertained to S&T.[9]

In addition to sharing a broad goal with the original *Hindsight* report, this paper also takes from it a similar unit of analysis, the CTE. *Hindsight* evaluations were based on a concept called an RXD Event. In that report, a RXD event has the predominant meaning of an event that "defines a scientific or engineering activity during a relatively brief period of time that includes the conception of a new idea and the initial demonstration of its feasibility."[10] There may be one or two such events in the development of a component or system, or a whole string of such events. In the case of basic research RXD events, the report distinguishes between undirected (curiosity driven) and directed (problem driven) work. Lastly, the final fabrication of the system component or device "may or may not involve an Event depending on the state of the technological art at the time of fabrication."[11] Please note that our signal events, CTEs, differ from *Hindsight's* RXD events in that CTEs can occur at any point in the life cycle. We leave open the possibility that CTEs might result from efforts that have utilized funds other than R&D. For more background on the *Project Hindsight*, see Appendix D of this report.

The importance of the three previous Defense & Technology Papers is the documentation of the Army S&T laboratories' contributions to the enabling of the weapons platforms. The CTE's noted in those reports influenced: 1) the Abrams main gun, gun accuracy, penetrating rounds, armor and crew protection, engine and drive chain, command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) and fire control; 2) the Apache helicopter engine and transmission, survivability and structural advances, avionics, fire control, weapons; 3) the Stinger and Javelin missiles seekers, guidance and control, and propulsion. For all these platforms, extensive modeling, simulations and data basing were contributed to the platforms. We will discuss modeling and simulation in this paper also. Another Paper was also recently published that continues the series of CTE documentation in Army Laboratories, which focused on CTEs that relate to sensors as opposed to platforms.[12]

Approach

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[9] Secretary Brown's letter in, *Project "Hindsight: Final Report"*, 135.
[10] *Project "Hindsight: Final Report"*, xiv.
[11] Ibid.
[12] Ratches, Chait, and Lyons, *Some Recent Sensor-Related Army Critical Technology Events*.

This present report on CTEs, focused on laboratory functions defined by the Commission, was generated based on interviews and correspondence with people closely associated with the R&D and program management. Since these selected topics are near-term achievements, it is still unknown what their ultimate significance and impact will be. We have chosen those contributory CTEs that appear to be the most probable success stories in the more distant future. We iteratively interviewed the participants of these programs and generated a final product. Even though the subject is near-term products, some have a rather lengthy past and are to some extent described. In appropriate cases, we had to contact technical people that were already retired, or otherwise had left government service. We attempted to contact all relevant contributors to these topics. Although we believe that each topic documented in the report is complete, we do suspect that there are other parts that we did not select or uncover. Follow-on reports will appear as necessary.

III. The Laboratory Functions

The 10 functions identified by the Commission were:

1. Infuse The Art of the Possible into Military Planning
2. Act As Principal Agent in Maintaining the Technology Base.
3. Avoid Technological Surprise and Ensure Technological Innovation.
4. Support the Acquisition Process.
5. Provide Special-Purpose Facilities Not Practical for the Private Sector.
6. Respond Rapidly in Time for Urgent Need for National Crisis.
7. Be a Constructive Advisor for Department Directions and Programs Based on Technical Expertise.
8. Support the User in the Application of Emerging Technology and Introduction of New Systems.
9. Translate User Needs into Technology Requirements for Industry.
10. Serve as A Science and Technology Training Ground for Civilian and Military Acquisition Personnel

In this analysis, each of the Commission's functions will be interpreted in order to elaborate on what is meant by each function title. Under each of the ten functions one or more relevant activities performed in an Army laboratory will be described documenting the performance of that function. In some cases the activities cited will be generic and apply to several or all Army laboratories. There will also be some very specific, more in depth, examples cited that refer to only one particular laboratory but are still relevant to more of the laboratories. The following section describes cited activities under the appropriate functions with relevant examples of CTE's demonstrating that function.

The Commission's report, after listing the functions of the Defense laboratories, goes on to list the attributes of a laboratory necessary to produce high quality and effective results. These attributes are:

- Critical mass of assigned work.
- A highly competent and dedicated work force.
- Inspired, empowered, highly qualified leadership.
- State-of-the-art facilities and equipment.
- Effective two-way relationship with customers.
- Strong foundation in research.
- Management authority and flexibility.
- Strong linkage to universities, industry, and other Government laboratories.

These are necessary, but not sufficient, guarantors of exceptional performance; there must also be close relations with the representatives of the Warfighter to ensure relevance and timeliness.

IV. Critical Technology Events Supporting Laboratory Functions

Function 1: Infuse the Art of the Possible into Military Planning

The thought behind this function is the surfacing of new, disruptive technologies that provide an expected/unexpected military capability. The cited examples cover the timeframe from the past to future candidates. There are four examples selected from Army S&T given in this section. The earliest of our sampling is the first electronic, general–purpose computer ENIAC, which was used by the U.S. Army. It also eventually had an enormous impact on modern life as one of the computers that formed the genesis of computing. Second, there is image intensification technology development that enabled night operations in ambient night time illumination without active sources for the first time. The first of these capabilities were used in the 1960s. A third example is one that is still an active research area with potential large impact on power for the next generation of Army combat vehicles; that is, research in silicon carbide (SiC) material and devices for vehicle power. The fourth area enables battlefield microbots, which, if successful, will enable new, as yet undetermined, Army combat capabilities for the future.

ENIAC Electronic General-Purpose Computer

The first high-speed electronic automatic computer[13] was the Electronic Numerical Integrator and Computer (ENIAC) funded by the Ballistic Research Laboratory (BRL) in the Army Ordnance Department in 1943. BRL had many world renowned scientists in its professional staff at that time, including two Nobel Laureates, Harold Urey, and Isadore Rabi.[14] The requirement to generate firing tables during World War II for Army munitions required intense and exhaustive calculations. Iterative calculations were needed for gunners to set elevation and azimuth of the cannon as a function of range, weather conditions, munitions, target, etc. The Moore School of Electrical Engineering at the University of Pennsylvania proposed an electronic numerical analyzer as an approach to handle the generation of these calculations. Two Ordnance Department officers, Colonel Paul Gillion and Captain Herman H. Goldstine, recognized the potential of the approach and a contract was awarded to the Moore School of Electrical Engineering for an electronic approach to generating the calculations **(CTE1)**. A working group including Moore School and Army scientists and engineers dedicated the ENIAC in February 1946 and it performed Army-relevant calculations for about ten years. Golstine got John von Neumann from Princeton's Institute of Advanced Studies interested and involved during the program. Von Neumann became interested in designing the architecture of the new electronic machine and today's modern computers that are ENIAC derivatives are generally referred to as "von Neumann machines."[15]

The ENIAC was originally designed as a collection of components that were wired together for each problem to be solved. This involved setting several thousand switches and wiring the units together with numerous coaxial cables and it took several weeks to reprogram the machine. It

[13] *50 Years of Army Computing from ENIAC to MSRC.*
[14] See Documenting Harford County History," *Aberdeen Patch*, August 16, 2011, available at <http://aberdeen.patch.com/articles/documenting-harford-county-history>.
[15] Ibid.

became apparent to the BRL S&Es early on that ENIAC could be used for a variety of calculations. Von Neumann suggested wiring the computer permanently with a program that takes numerical instructions from the switches on the function tables. This became an early version of machine code **(CTE2)**. Machine code reduced setup time for new programs from weeks to several hours. This task was carried out by BRL mathematicians.[16]

Besides the firing table calculations, the Army developers of ENIAC addressed many new computational problems for the first time. For example, implosions for the hydrogen bomb development, aerodynamics, supersonic flows, guided missiles, and interior ballistic compression and explosion.[17] The Army program quickly evolved after the war and several new versions of digital computers were developed, including Electronic Discrete Variable Automatic Computer (EDVAC), the first computer with internally stored programs **(CTE3)**. The new computers quickly were applied to new computational problems, such as weather prediction, atomic energy research, thermal ignition, cosmic ray studies, and wind tunnel design. Army BRL employees did the logic design, back panel wiring and assembly, and pioneering software, and were among the first to use FORTRAN, a programming language, on a computer other than an IBM machine. In fact, BRL developed the FORAST language as a precursor to FORTRAN. Calculations were also done in support of the Manhattan Project.[18] Probably one of the most significant contributions of the first Army scientists to the new computer technology was the identification and demonstration of the new computer capabilities to solving many other problems **(CTE4)**. Given where computer technology has gone today and the pervasiveness of it in the modern world, ENIAC is the poster child for "infusing the art of the possible" into all aspects of planning, not just for military applications.

Night Fighting Capability

Armies since the beginning of time have wanted to be able to fight at night. Night operations without any artificial illumination under a partial or no moon, or in overcast starlight, can be significantly degraded. Illumination from the moon can provide some night fighting capabilities, as can searchlights, which have been experimented with since the mid-19th century. The use of material that is sensitive to visible and ambient near infrared radiation can be a useful front entrance for a night time imaging sensor. However, a gain mechanism is required in order to present a useful image to soldiers. The gain approach for First Generation image intensification (I^2), fielded by the Army, was to cascade three near infrared (NIR) 40 mm photocathodes of silver-cesium oxide (S-1) and multialkali-cesium (S-20) photocathodes with commensurate phosphor and electrostatic focusing elements **(CTE5)**. A gain of 10,000 was realized in early devices in the 1958 timeframe.[19] This innovation resulted in the development and fielding of the rifle-mounted Small Starlight Scope (ANPVS-2).[20] An infrared or "pink" searchlight was still needed for long-range observations. In second generation I^2, an 18 mm higher efficiency S-25

[16] Harry Reed, Subject Matter Expert, Ballistics Research Laboratory, email on February 28, 2013.
[17] Harry Reed, interviewed by authors, February 25, 2013.
[18] *50 Years of Army Computing from ENIAC to MSRC*, Thomas J. Bergin, Ed. (Aberdeen Proving Ground, MA: Army Research Laboratory, September 2000), available at <www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA431730>.
[19] Briefing chart from John Pollard, Senior Scientist, Night Vision and Electronic Sensors Directorate.
[20] "Thermal and Night Vision Weapon Sights and Scopes," *Moro Vision*, undated, available at <www.morovision.com/weaponsights.htm>; "Night Vision and Optics," *What A Country*, undated, available at <http://whatacountry.com/nightvisionandoptics.aspx>.

(same material as S-20) photocathode with extended red and reduced blue response was implemented with a microchannel plate (MCP) for resultant gain of 100,000 and was fielded in 1975 **(CTE6)**. The incident NIR photons from the scene interact with the photocathode (PC) fabricated on an MCP, and electrons are ejected from the PC into the MCP. MCPs have tubular holes, so that secondary electrons collide with the surface of the holes and cause higher order electrons to be ejected. The introduction of an electric field in the MCP can accelerate the electrons to give further gain. When focused on a display, a recognizable image is presented to the Soldier. Third generation image intensification in 1984 replaced the S-25 photocathode with a gallium arsenide (GaAs) photocathode **(CTE7)** that had a much higher photon gain of ~100,000.[21] The small, high sensitivity, and gain configuration of third generation enabled Night Vision Goggles (NVG) for helmet mounted sensing and a completely passive system useful at illumination levels of overcast starlight.[22]

The infusion of night vision technologies into the U.S. Army's repertoire changed the way the Army planned operations and prosecuted war. These generations of image intensification, as well as the other night vision technology of thermal imaging, were the products of collaborative R&D between industry and government laboratories and resulted in the first truly passive night vision technology for the Warfighter. It was initially fielded in Vietnam in the 1960s.[23] Ever since the fielding of the complete suite of night vision sensors across the force, the American Soldier has preferred to fight at night instead of day, and helped to infuse their use into nearly every platform in the Army arsenal.

During the research and development of new concepts for the Army, such as night vision, extensive field testing is required in order understand the effects of realistic operations on new system concepts that are being conceived. These laboratory designed tests routinely have participation by soldiers as test subjects and officers for consultation on operational test designs. These field tests infuse the Art of the possible into future military planning by both exposing the Soldier to what is being developed for them and excite the officers with the new tactical possibilities. Development of I^2 technology through collaboration between Army laboratories and industry evolved to handheld night sights **(CTE8)** for weapons sighting and image intensifier goggles for maneuver and helicopter pilotage **(CTE9)**. These capabilities make completely covert night operations possible and introduce new doctrinal concepts for innovative tactics.

Silicon Carbide (SiC) Electronic Power Devices

The demands for increased power on combat vehicles continue to escalate. Today's power requirement for the Ground Combat Vehicle (GCV) is 1500 horsepower, the same as for the Abrams tank.[24] The power budget continues to expand due to the desire for more vehicle capabilities, including directed energy systems, electromagnetic survivability, and lethality systems such as electromagnetic (EM) Armor and the development of efficient electrical power

[21] Chart from John Pollard, Senior Scientist, Night Vision and Electronic Sensors Directorate.
[22] John Pollard, Senior Scientist, Night Vision and Electronic Sensors Directorate, discussion on February 26, 2013.
[23] "History," *Night Vision and Electronic Sensors Directorate*, homepage, undated, available at <www.nvl.army.mil/history.html>.
[24] "M1 Abrams Tank–Allison Transmission," *Diesel Power*, February 2009, available at <www.dieselpowermag.com/features/0902dp_m1_abrams_tank/>.

trains. Whereas present Army combat vehicles provide very little electrical power, the need for advanced capabilities is driving requirements for large electric generators and compact efficient power conversion to provide appropriate and useable power for these new capabilities. SiC technology is a candidate technology that ARL has been investigating as a solution to provide this power conversion for high vehicle power **(CTE10)**. SiC devices can operate under extremely high voltage (~20KV) and current with an efficiency of 97-98 percent compared to silicon devices (7-8KV) with 93-95 percent. The higher efficiency provided by SiC makes more power available in a combat vehicle. Further, SiC devices use less material compared to silicon (Si) devices, and are consequently smaller than Si devices. The ability of SiC to handle high current densities provides for smaller packages for a given density. SiC devices also operate at higher temperatures of up to 300C, compared to Si devices that operate only to 125C. The higher operating temperature permits smaller and more efficient thermal management systems, and the ability to handle more current in a smaller system configuration, which is critical for combat vehicles.

In 1990-91, ARL investigated SiC to provide radiation hard semiconductors for logic circuits. The research was directed towards improving the starting material characteristics by reducing the micropipes, which are defects that occur during crystal growth. Micropipes are voids that that can grow all the way through the Si to the substrate. More recently in the 2000s, the emphasis has moved to reducing cost and developing designs and technologies to enable voltage controlled switches for power conversion. The ability for SiC devices to operate at higher temperature and handle more current or voltage allows smaller conversion systems. The ability for SiC devices to efficiently handle more current, at higher temperatures is essential to ground combat vehicles and other mobile platforms. Additionally, SiC can operate at higher switching frequencies than current technologies, further reducing component volume and weight through smaller passive components. The expanded SiC trade space of efficiency/operational temperature/ reliability/ power density is extremely attractive to ground combat vehicle designers. Moreover, if the Army's proposed Ground Combat Vehicle uses a hybrid design, of a fuel driven engine to electrical conversion, then SiC will be an enabling technology.

New advances in potential combat vehicle technologies, such as directed energy and EM armor require high voltage power switching. SiC power supplies and converters that are more compact will be necessary for success in meeting the Army's vision of a new combat vehicle. As another critical enabler, SiC components cost is currently 3 times that of Si. Efforts by ManTech, which is funded by the Office of the Secretary of Defense within the Pentagon, **(CTE11)** and led by ARL, are underway to further reduce the cost difference to 1.2-1.5X Si costs. With these cost reductions, the Army S&T base has infused the potential for a new combat vehicle with Army desired capabilities into military planning.

Battlefield Microbots

The fourth and final example of a more far off research effort at the ARL and could lead to potentially new, unimagined battlefield capability is micro-autonomous systems (microbots). Whereas battlefield robots under development are visualized as small vehicles with a package, such as sensors,[25] Army research is addressing research for robots on the sub-microscale that have the ability to carry microsensors. Recently a thrust driven microbot using nanoporous energetic silicon has demonstrated vertical thrust of approximately 8 centimeters launch with a charge of 250 μJ of kinetic energy. This microrobot uses a hybrid integration approach to assemble on-board control, sensing, power, and actuation on a polymer chassis.[26] A whole family of microbots **(CTE12)** can be imagined to perform multitudinous combat functions.

Function 2: Act as Principal Agent in Maintaining Technology Base

Once a technology has demonstrated its value on the battlefield, the Army laboratories must help maintain the technology base and enhance it should there be no potential commercial market that can induce further industrial investment. Additionally, it is incumbent on the Army laboratories to identify when or where there are inadequacies in the base and stimulate additional research. An expansion of the technical understanding of the materials, devices, and systems that is dependent on the underlying science and technology would be an example of legitimate stewardship of the tech base. Modeling with requisite empirical data for verification and validation is such a way to maintain a technology base, for example for protection and lethality materials and electronic materials and devices.

Lethality and Protection

The ARL-Weapons and Material Research Directorate (WMRD) has a long history of maintaining core competencies in ballistics sciences and materials sciences focused on U.S. Army needs along with a cadre of highly educated scientists and engineers. The accomplishments were enabled by the ARL cutting edge high performance computing (HPC) capability and visualization environment as well as extensive and unique WMRD experimental facilities. The professionalism and quality of the WMRD staff is the foundation for the long track record of accomplishment in the relevant science and technology and the consequent impact on U.S. Army capabilities. The knowledge and understanding embodied in the WMRD has led to many significant transitions to a Program of Record (POR) or fielded in recent years representing superlative maintenance of the critical Army technology. These are ten examples of recent accomplishments.[27]

[25] The Micro Autonomous Systems Technology (MAST) Collaborative Technology Alliance led by ARL-SEDD.
[26] W.A. Churaman, L.J. Currano, C.J. Morris, J.E. Rajkowski, and S. Bergbreiter, “The First Launch of An Autonomous Thrust-Driven Microbot Using Nanoporous Energetic Silicon,” *Journal of Microelectromechanical Systems* 21, no. 1 (February 2012), 198—205.
[27] These 10 examples were written by Peter Plostins, Subject Matter Expert, ARL-WMRD.

1. Armor Technology for Defeat of IED Threats **(CTE13)**: Using computational and experimental terminal ballistics, threat exploitation, novel defeat mechanisms, armor materials and manufacturing science expertise for armor materials, improvements resulted in Armor Survivability Kit (ASK), High Mobility Multipurpose Wheeled Vehicle Interim Frag Kits 5 and 6, Frag Kit 6 for Tactical Wheeled Vehicle, Mine-Resistant Ambush Protected vehicles Expedient Armor, Spall Curtains, Thrown-Object Protection System and Specialized Bar Armor. Transition was made to Tank Automotive Research, Development and Engineering Center (TARDEC), Joint Program Office Mine-Resistant Ambush Protected, Program Manager-LTV steel, Program Management-Stryker, the Joint IED Defeat Organization (JIEDDO), U.S. Army Ground Systems Industrial Enterprise, and the Army Material Command Depot System (2003-2010).

2. Explosive Reactive Armor (ERA) Technology for U.S. Combat Vehicles **(CTE14)**: Based on computational and experimental terminal ballistics, threat exploitation, explosives response and behavior, and impact dynamics improvements in reactive armor resulted in appliqué kits for major U.S. Army Ground Vehicle Systems. Transition was made to Program Manager-Abrams, TARDEC, Armaments Research and Development Center, Program Manager-Bradley, Program Manager-Stryker, BAE Systems, General Dynamics Land Systems (GDLS), General Dynamics Armament and Technical Products, and the Ensign Bickford Aerospace & Defense Industry (1992-2008).

3. Crew Survivability in Underbody (UB) IED attacks **(CTE15)**: Based on computational and experimental terminal ballistics, threat exploitation, soil mechanics, multiphase blast loading, advanced materials and manufacturing science and biomechanics of human injury, vehicle improvements resulted in UB Kit for the Abrams, UB Kit for the Stryker, UB kit for the Military All-Terrain Vehicle, seat upgrades for the Stryker, Bradley and Abrams. Transitions were made to Program Executive Officer-Ground Combat System, Program Manager-Bradley, Program Manager-Abrams, Program Manager-Stryker, Program Manager-Future Combat Systems, GDLS, BAE Systems, TARDEC, JIEDDO, and Internationally to The Technical Cooperation Program and North Atlantic Treaty Organization allies, such as Britain, Canada, Australia, Germany, Italy, and France (1997-present).

4. Transparent Armor **(CTE16)**: Based on defects and failure mechanisms in amorphous and polycrystalline ceramics, high strain rate response of glass and ceramic materials, novel processing technology for laminates, plasticity in amorphous and crystalline materials, polymer chemistry and chromophore chemistry, improvements resulted in technologies for laser eye protection for vehicles and personnel, transparent armor and vision blocks for vehicles, transparent armor for rotorcraft, abrasion resistant coatings for air vehicles and radomes. Transition was made to Program Executive Office Combat Systems/Combat Service Support, Program Executive Office-Ground Combat Systems, the Natick Soldier Research, Development, and Engineering Center (NSRDEC), the Army Missile Research, Development and Engineering Center (AMRDEC), U.S. Special Operations Command, the Office of Naval Research, Program Executive Officer for modeling and simulation, and BAE Systems (1992-Present).

5. Helmet Pre-form Assembly Machine **(CTE17)**: Technology for Next Generation Warfighter Head Protection: Based on Thermoset crosslink polymer chemistry, compression molded thermoset-based aramid composite material science, and thermally bonded fiber reinforced material science improvements resulted in the Enhanced Combat Helmet (ECH), FAST (Future Assault Shell Technology) Helmet, and the MARITIME Helmet. Transitions were made to NSRDEC, the U.S. Army ManTech Program, and the Program Executive Officer-Soldier (2005-2011).

6. Environmentally Friendly Chemical Agent Resistant Camouflage Coatings (CARC) **(CTE18)**: Based on polyurethane chemistry, aqueous dispersible hydroxyl functional polyurethane, cross linked polymer chemistry, thermal and radiation physics, improvements were made in water dispersible chemical agent resistant coatings. Transitions were made to Army Environmental Command, the Strategic Environment Research and Development Program (SERDP), the Environmental Security Technology Certification Program (ESTCP), and all U.S. Marine Corps and Army Vehicle Program Managers (Date: 1995-Present).

7. Advanced Gun Accuracy: Profile Verification Program (PVP) **(CTE19)** for Abrams Main Battle Tank: Based on in-bore projectile non-linear time dependent structural dynamics, time dependent gun dynamics, launch and flight dynamics and tank gun accuracy improvements resulted in uniform tank gun barrel profile manufacturing technology. Transitions were made to U.S. Army ManTech, Armaments Research and Development Center (ARDEC)-Benet Labs, Program Manager-Abrams, and Program Manager-Tank and Medium-caliber Armament Systems (1992-Present).

8. Development of Multidisciplinary Computational Fluid Dynamics and Structural Dynamics Models with Application to Small-, Medium-, and Large-Caliber Weapons Systems **(CTE20)**: Based on flight vehicle structures, propellant chemistry, multidisciplinary high performance computing (fluid structure interaction, finite rate chemistry, non-linear coupled computational fluid dynamics/rigid body dynamics), gun-projectile interaction, exterior ballistics (aerodynamics), launch-hardened electronics, and guidance/navigation/control, modeling and simulation capabilities improvement resulted in Multidisciplinary Next Generation Enterprise Network (NGEN) Interior Ballistics Code, "Digital Virtual Aerodynamics Range," DYNA3D time dependent gun dynamics model, and non-linear micro adaptive flow control. Transitions were made to Program Manager-Combat Ammunition Systems, Program Manager-Maneuver Ammunition Systems, ARDEC, AMRDEC, and Program Executive Office-Soldier (1992-Present).

9. Small Caliber Lethality Technology **(CTE21)**: Technology underpinning the development of 5.56 mm M855A1 and the 7.62 mm M80A1 guns was developed based on terminal ballistics to include penetration mechanics, interior ballistics, launch and flight dynamics, structural dynamics, vulnerability, and lethality system analysis. The 5.56 mm is the only green ammunition system fielded to date in the world and delivers consistent effect against soft

targets, with significant increase in ability to defeat hard targets at extended ranges It has increased effectiveness at extended distances. with no increase in cartridge weight, has reduced muzzle flash and has lead-free design which provides environmental benefit. Transitions were made to Program Executive Officer–Ammunition, Project Manager–Maneuver Ammunitions Systems, ATK, ARDEC, St. Marks Powder, Program Management–Soldier Weapons, the U.S. Army Intelligence Center, Maneuver Center of Excellence – Sensor Research Division, the U.S. Marine Corps, Army Evaluation Center, Developmental Test Command, the Office of the Secretary of Defense Defense Operational Test & Evaluation, the Center for Health Promotion & Preventative Medicine, and Army Materiel Command (2003-present).

10. Technology for Experimental Projectile Dynamic Flight Motion **(CTE22)**: Based on MEMs Sensor technology, non-linear signal processing and analysis, magnetic navigation and sensing, RF electrodynamics, non-linear flight dynamics and telemetry. Improvements have resulted in U.S. Patent #6,349,652 DFUZE-real time experimental full state estimation of non-linear flight dynamics and guidance navigation and control state and autopilot function and earth field magnetic navigation capability. Transitions were made to Project Manager–Maneuver Ammunitions Systems, Project Manager–Combat Ammunitions Systems, the U.S. Marine Corps, the Office of Naval Research, the Naval Service Weapons Center, Project Manager–Maneuver Ammunitions Systems (DARPA), ATK, BAE Systems, Goodrich Aerospace, Synetics, ARDEC, AMRDEC, NASA (1992-Present).

Enterprise for Multiscale Research of Materials

The Army has critical and unique needs for materials for protection (armor) and electronics. Protection materials are required for new combat vehicle survivability against advanced munitions. Electronic materials in the power and energy application areas are needed to enable lower temperature, higher energy/power and long life electronics in constrained Army vehicles, and small, long life batteries for individual soldiers. Advances in high performance computing and power, experimental techniques, materials characterization and processing have set the stage for major advances in materials science.

ARL's Enterprise for Multiscale Materials Research acts as a principal agent for maintaining and enhancing the technology base for protection, or materials in high-loading rates environments, and electronics material research. Recently two Collaborative Research Alliances (CRAs) have been awarded in "Extreme Dynamic Environments" and Multiscale Modeling of Electronic Materials" **(CTE23)**. Besides the Army relevance and significance, these CRAs support four science initiatives for the Office of the Secretary of Defense in Engineered Materials, Nano Science and Engineered Materials, Quantum Systems, and Synthetic Biology. They are also related to the material priorities and scientific foundation for the Materials Genome Initiative and Integrated Computational Materials Engineering (ICME). The collaboration in this initiative has significant in-house efforts and will realize "materials by design" for Army critical materials.

Two Workshops prior to these awards were held by ARL with industry and academia in order to assess the state-of-the-art in modeling in the community and determine what should be done in these areas and priorities. One on Multiscale Materials Behavior in Ultra-High Loading Rate

Environments was held in Towson, Maryland in 2008, and one on Multiscale, Multidisciplinary Modeling of Electronic Material in Fairfax, Virginia in 2010.

The two CRAs and the internal ARL materials research efforts form the components of the ARL Enterprise in Multiscale materials research. The ARL roles in the enterprise are research leadership and consortium management, crosscutting research in the five core areas, developing computational materials by design capabilities via sharable physics-based predictive tools, integration of advanced experimental validation capability, and the transition from research to technology. ARL's significant research facilities will provide experimental results and data to support validation and verification of analytic models to be developed under the CRAs. The CRA on Materials in Extreme Dynamic Environments was awarded to an academic team led by Johns Hopkins University with the University of Delaware, Rutgers University, and the California Institute of Technology and addresses modeling of metals, polymer, ceramics and composites. The Multiscale Modeling of Electronic Materials CRA was awarded to the University of Utah (lead), Boston University, and Renssellaer Polytechnic Institute, and will address electrochemical devices, hybrid photonics, and heterogeneous metamorphic electronics.

The ultimate goal of this multiscale modeling effort is a transformational materials science enabling materials by design for the future Army. A multidisciplinary coupling, scale bridging, and transformational material science will enable a fundamental change in the innovation space through multidisciplinary coupling, scale bridging and multiscale exploitation **(CTE24)**. The concept is to design materials and predict performance by developing material models that connect in a hierarchical manner from the atomistic to molecular to micro to meso to continuum to material assemblies to systems. That is, relate the response of structural and electronic materials across critical length and time scales to specific properties. This activity amounts to maintaining the tech base for the materials most critical to the Army warfighting capabilities.[28]

Function 3: Avoid Technological Surprise and Ensure Technological Innovation

Avoiding Surprise

The S&T programs that DOD maintain includes a laboratory system, as well as provides grants and contracts to researchers outside the Department. The DOD employs some 100,000 people with degrees in science and technology (the S&E workforce) of whom perhaps one third are involved in the 21 DOD laboratories included in the study performed by the Institute for Defense Analysis.[29] The others are involved in some way with technical work, such as support to acquisition Program Managers, testing and evaluation, awarding and overseeing technical grants to academia and industry, and management of the foregoing. In a recent study of the effect of globalization of science and technology, it is estimated that perhaps 15,000 of these are in the in-

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[28] See "Materials in Extreme Environments, *Army Research Laboratory*, available at <www.arl.army.mil/www/default.cfm?page=1419>; "Electronic Material," *Army Research Laboratory*, available at <www.arl.army.mil/www/default.cfm?page=1418>.

[29] Jocelyn M. Seng and Pamela Ebert Flattau, *Assessment of the DOD Laboratory Civilian Science and Engineering Workforce*, IDA Paper P-4469 (Alexandria, VA: Institute for Defense Analyses, 2009), available at <www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA506429>.

house laboratory workforce that is concerned with basic and applied research. These are roughly matched by another 15,000 on grants and contracts for the in-house program.[30]

These pools of experts have a responsibility for remaining current in world-wide development in their disciplines. This is a resource for avoiding technological surprise. One of the occupations of researchers is reading the literature in their fields; another is attending scientific meetings and visiting other laboratories.[31] The granting entities (Office of Naval Research, Army Research Office, and Air Force Office of Scientific Research) interact continually with their grantees and also read proposals (that may not be funded but which describe the latest thinking) and so are aware of the latest developments at the frontiers of knowledge.

There are many examples of military programs avoiding surprise either by inventing and innovating itself or by quickly taking advantage of developments arising internally, or taking advantage of external developments. In the development of the Abrams Main Battle Tank, 55 CTEs were identified that contributed significantly to its successful fielding.[32] Three examples are the armor, the main gun, and armor piercing munitions. The armor arose from a combination of developments in the United Kingdom immediately shared with the U.S. Army. Improvements were made by the Army's armor experts using the latest in welding technology and the use of extra heavy elements. The main gun succeeded a 105mm cannon based on British technology that had been used on the M60 Patton tanks and used in the earliest version of the Abrams. The new 120mm gun was first developed in West Germany and brought to the United States specifically for the Abrams. The Army laboratories perfected the design and especially the factory production processes.

The most notable development in munitions for the Abrams is the kinetic energy, long rod penetrator first designed for the 105mm gun and perfected for the 120mm gun on the Abrams. This work depended on years of research on penetration mechanics and thousands of sub-scale experiments. This was made possible by decades of investment in Army facilities and the expertise of the technical staff. It is the conventional wisdom today that the Abrams is considered to be the world's most effective tank. (It was not always thus—in World War II, the Germans had the best tanks in their Panzer divisions. The US countered this with an advantage in the sheer numbers of tanks that were able to be manufactured.)

Work by the U.S. intelligence agencies reinforces the information available to the S&E work force. The Army generally knew what the potential enemy was developing in terms of performance and materials. The intelligence groups on occasion would obtain a captured system and allow the laboratories to analyze and perhaps reverse engineer such a system. This partnership between the laboratories and the intelligence community has been very effective in avoiding surprise. Another set of examples is in the development of the Stinger and Javelin missiles. For these two systems the 35 CTEs were identified.[33] Industry accounted for somewhat

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[30] Timothy Coffey and Steven Ramberg, *Globalization of S&T: Key Challenges Facing DOD*, Defense & Technology Paper 91 (Washington, DC: Center for Technology and National Security Policy, February, 2012), 17.

[31] See "Assessing and Predicting for Army Science and Technology," in John W. Lyons, Joseph N. Mait, and Dennis R. Schmit, *Strengthening the Army R&D Program*, Defense & Technology Paper 12, 28—46 (Washington, DC: Center for Technology and National Security Policy, March 2005).

[32] Chait, Lyons, and Long, *Critical Technology Events in the Development of the Abrams Tank-Project Hindsight Revisited*.

[33] Lyons, Long, and Chait, *Critical Technology Events in the Development of the Stinger and Javelin Missile Systems-Project Hindsight Revisited.*

more than half of these. Because of the Army's sustained investments in missile technology and the many allied technologies important for the missiles, industry was able to turn to the Army S&Es and facilities to test prototype missiles and aid in readying them for fielding.

Ensuring Innovation

"Invention" is conceiving of something new and reducing the idea to practice. The U.S. Patent Office requires that there be some evidence of how the idea will be used. In the 19th century the Patent Office required that an inventor accompany their application with a working model, however, small. Nowadays one has to sketch out a concept and show some evidence of building a prototype, isolating and characterizing a new substance, or demonstrating a new process. "Innovation" may include the entire process of inventing and taking to market something new; in other definitions it covers only the process after the invention and readying it for engineering, production, and fielding. In the private sector this is called going to market or commercialization.

Long-term basic research keeps the S&T program at the knowledge frontiers and either uncovers new science and new technology or puts the Army in position to harvest same because of the staff's participation in the broader community. The Army Research Office has supported investigations in laboratories external to the Army that led to 17 Nobel prizes (as of 2005) in such areas as the development of the maser (and laser), laser spectroscopy, discovery of Fullerenes, and of conductive polymers.[34] It was an Army laboratory that funded the development of the first modern reprogrammable computer, the ENIAC or Electronic Numerical Integrator and Computer (**CTE1**).

The RAND report referenced in the previous paragraph has a discussion of the current status of the Army S&T program in terms of the "basic, or exploratory research, conducted in Army laboratories … in the Army Materiel Command (AMC) from which cutting-edge discovery, invention, and innovation might emerge." The idea is that by performing basic research, especially high-risk, long-term work, with no particular end-use system in mind, new ideas for new systems may arise. These, in turn, can be linked to needs and requirements for new Army capabilities defined by the Army's Training and Doctrine Command. The RAND panel considers that Army S&T at AMC has become too short range. A strong program in basic research, in addition to providing new opportunities for the Army, also has other benefits. The presence in the laboratory of people doing this kind of work helps to ensure that the more applied work will be at the state-of-the-art. It also helps in recruiting new graduates, including, importantly, new post-doctoral fellows.

The extent to which the Army laboratories and, more broadly, the external programs, support innovation depends on several factors: 1) the funding required to support the investigators; 2) presence of experienced and well-qualified researchers; 3) special equipment and facilities needed; 4) clear statements of needed future warfighting capabilities; and 5) a management strongly supportive of basic research. Despite the criticisms noted above, the Army does have a good program of basic research as exemplified by its external programs such as the Collaborative Technology Alliances, and the several University Affiliated Research Centers. Sometimes

[34] Gilbert Decker, Robert A. Beaudet, Siddhartha Dala, Jay Davis, William H. Forster, George T. Singley III, *Improving Army Basic Research: Report of an Expert Panel on the Future of Army Laboratories* (Santa Monica: RAND, 2012).

innovation results from work done by engineers attempting to overcome problems encountered in manufacturing and fielding new systems. In other cases complaints from soldiers as they use the system may be accompanied by suggestions for correcting the problem. Such has been the case for the wars in Iraq and Afghanistan. When, in Iraq the improvised explosive devices (IEDs) were encountered, the forces needed additional protection for HMMWVs, Stryker vehicles, and the like. Because of the deep expertise at Aberdeen Proving Ground, new bolt-on armor plates were quickly devised **(CTE25)** and the vehicles received the additional protection. The same was true for individual body armor.

In normal times the work of the laboratories proceeds at a steady pace but when the DOD goes to war, everything is much accelerated and focused on immediate problems on the battlefield. Examples abound. In the case of IEDs, the laboratories and the Corps of Engineer had to devise an approach and to adopt new techniques coming from work at the laboratories and in the activities of the Joint IED Defeat Office that was sponsoring studies at many laboratories in and out of the DOD. New techniques for sensing incoming munitions and determining their vectors had been under development for some time but the wars in the Southwest Asia sped up that work and new systems were fielded post haste **(CTE26)**. (See more in the section on Function 8—Support the User in the Application of Emerging Technology and Introduction of New System).

Likewise when the Pentagon was partially destroyed on September 11, 2001, the Corps of Engineers provided technology for blast resistance for the restored structural members and the windows **(CTE27)**. The Medical Research and Materiel Command's work on casualty care was greatly accelerated by the two wars. Notable developments were made in controlling bleeding **(CTE28)**, treatment for shock **(CTE29)**, dealing with diseases found in the desert **(CTE30)**, devising new approaches to traumatic brain injuries **(CTE31)**, pain management **(CTE32)** and more similar CTEs are documented.[35] (See Function 6—Respond to National Crisis, for more information).

Function 4: Support the Acquisition Process

This function is central to the underlying mission of the Defense laboratories stated above. By policy, and perhaps necessity, the nation relies primarily on the private sector for the development and production of military equipment. The laboratories provide the acquisition agents an in-house, technologically qualified agent to oversee or evaluate the performance of the industrial developer as required to ensure the design is technically sound, will satisfy performance requirements, and is producible and affordable.[36]

There are many examples of supporting the acquisition process by the Army Laboratories and Centers. To give any examples would be only be scratching the surface of all the examples that could be mentioned in this document and surely some impressive acquisition support would be left out. Whether it is vehicles, aircraft or individual Soldier systems, the supporting development and technical advice occurs consistently along the acquisition path to fielding.

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[35] Richard Chait, Albert Sciaretta, John Lyons, Charles Barry, Dennis Shorts, and Duncan Long, *A Further Look at Technologies and Capabilities for Stabilization and Reconstruction Operations*, Defense & Technology Paper 42 (Washington, DC: Center for Technology and National Security Policy, September 2007).
[36] Adolph, *Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories,* C-1.

The Research, Development, and Engineering Command, ARL, and the Research, Development and Engineering Centers supply matrix support to the Army Project Managers and Project Executive Officers, as do the Corps of Engineers Centers Of Excellence's, and the Medical Research and Materiel Command. Any number of Subject Matter Experts from the Army laboratories in any given year is resident at the Manager and Executive Officer facilities. The laboratory S&Es supply critical expertise to the generation of the source selection package, contribute to the evaluation of proposals submitted by industry and perform evaluation of prototypes. Not only do these Army S&Es supply the requisite technical knowledge to the solicitation and award process, but also provide the in-house understanding of the Army requirements.

There are a number of specific, generic roles by which the Army laboratory subject matter experts support the Manager and Executive Officer acquisition process. Examples of these roles are given in the following[37]:

1. Act as a Matchmaker to facilitate discussions among users, industry, and academia.
2. Support the consideration of alternative approaches with more or less risk, and examine the planned transition.
3. Act as an enabler by fully exposing the Project Manager to the technology for their application requirement.
4. Assess the future developments of the technology after the requirements have been met.
5. Educate the Project Manager on new technology developments and track them.
6. Acquaint the Project Manager with field test issues for the technology and suggest optimal test sites (for example, the Army Test and Evaluation Command).

After contract award, the in-house S&E's can remain in the management shop to execute, oversee, or otherwise contribute to the program. In some programs this may also include evaluation on Army test beds and even testing prototypes in the field.

While an RDEC supports the acquisition process in very direct and visible ways, ARL also supports system acquisition but, typically, from more of the research end of the process. An example is the direct way the Sensors and Electron Device Directorate of ARL (ARL-SEDD) enabled a more cost effective process for infrared focal plane arrays (IR FPA) fabrication in support of the thermal imaging night vision systems acquisition. See subsection (b) below. Topic (a) below is an example of how S&T involvement in the Apache program added a whole new technology to the helicopter due to unforeseen environmental conditions encountered in Europe prior to fielding.

a) Image intensifiers (I^2) and thermal imagers were designed initially to provide night vision for ground maneuver and targeting. Image intensified goggles were fielded to provide night pilotage for the Apache helicopter prior to thermal imaging technology because of the maturity difference between the two technologies. However, a field test performed in Germany by the Night Vision Lab in the 1980s demonstrated that the two night vision technologies optimally performed pilotage under different orthogonal environmental

[37] Eric Zipperer, member of Project Executive Office—Soldier Office, interviewed by authors, March 8, 2013.

conditions **(CTE33)**. That is, when light level was insufficient for I^2 operation, the infrared background target signature (temperature difference) was sufficient to perform the mission. Conversely, when the infrared signatures of the background were low, the light level tended to be sufficient for I^2 operations. Not only were I^2 and thermal imaging complimentary, but they were both necessary to enable night pilotage under a greater range of background conditions. As a result, the Project Manager and Project Executive Officer for Apache mandated that night vision goggles would be carried in the helicopter in addition to the integrated thermal Pilotage Night Vision Sensor (PNVS).[38]

b) Recently, there was concern over the cost of infrared focal plane arrays (IR FPAs). A major cost driver was the substrate upon which the IR detector material was grown. The substrate is composed of CdZnTe which is very compatible to growth of mercury cadmium telluride (HgCdTe or MCT) on its surface. HgCdTe is the IR sensitive material. However, CdZnTe is very expensive for a substrate and is only available from a foreign source. Research at ARL-SEDD on growing MCT on much less expensive silicon wafers has resulted in a process that enables the growth of MCT on Si at very much less cost and has overcome the dislocation density that in the past has resulted in inferior IR FPAs grown on silicon. The process is called temperature cycling anneal (TCA**)**[39] **(CTE34)** and reduces the defects in the hybrid device to levels that permit growth of low defect detector arrays. The process has been transitioned to the IR FPA manufacturers, Raytheon and Teledyne through a manufacturing Technology program, ManTech, run by the Night Vision and Electronic Sensors Directorate (NVESD).[40] By maintaining the tech base at ARL, the manufacturing of affordable IR FPAs has been ensured for the PM program in next generation thermal imaging.

Function 5: Provide Special-Purpose Facilities Not Practical for the Private Sector.

This function includes large field test ranges and also unique laboratory test/measurement bench facilities used by the government to verify and validate contractor performance claims. Government developed and controlled models and simulations would also be included in this function.

Field Test Ranges

Frequently, unique large test range facilities are needed to acquire data unique to military systems performance. These test range facilities are not practical for private investment by industry. Obviously, weapons platforms, systems, sensors, munitions, and other attributes require quantification of their performance in realistic environmental conditions and test ranges to do this would be prohibitively expensive for private industry to acquire and maintain. Consequently, there are test ranges owned by the Army to test this total systems performance. Examples are White Sands Missile Range, NM, Aberdeen Proving Grounds, MD, Yuma Proving, Ground, AZ,

[38] This decision was witnessed personally by James Ratches during the Project Management meeting.
[39] S. Farrell, M. V. Rao, G. Brill, Y. Chen, P. Wijewarnasuriya, N. Dhar, D. Benson, and K. Harris, "Effects of Cycle Annealing Parameters on Dislocation Density Reduction for HgCdTe on Si," *Journal of Electronic Materials*, 40, no. 8 (2011), 1727—1732.
[40] Gregg Brill, Subject Matter Expert and inventor, interviewed by authors, February 25, 2013.

Ft. A.P. Hill, VA, Huntsville, AL, Ft. Polk, LA, Ft. Hunter Liggett, CA and others. However, not only are the facilities unique, but they may have to be in unique locations for special weather effects, terrain, and environmental conditions. A good example of this requirement is the necessity to quantify environmental effects and distributions in militarily important locations, such as the desert. The unique requirement is mandated when variables such as atmospheric propagation, soil characteristics, unique target sets, lines-of-sight distributions, etc. are peculiar to the intended geographic deployment location. The point here is not that these effects need to be quantified for any weapon, which they are, but the unique characteristics associated with the envisioned location on the globe may cause severe degradation on performance which requires quantification. Thus, the Government or Service needs to operate instrumented test ranges that can be used for system level quantification on new, prototype systems. Extremely important to the wars in Iraq and Afghanistan were special purpose test facilities owned by Army laboratories that contained land mine test facilities.

A particular example of the need to test under unique weather considerations was the need to evaluate First Generation thermal imaging under highly attenuating haze and fog conditions. The first thermal imagers on tanks and helicopters were to be deployed to the Fulda Gap region of Germany in anticipation of a Soviet attack across the Gap in the early 1970s. The natural weather in Central Germany was considerably degrading and that degradation to infrared transmission had to be quantified to determine of weapons effectiveness under the naturally occurring, local atmospheric conditions, e.g., hazes and fogs. Existing data on atmospheric degradation under these severe naturally occurring conditions was minimal for any quantitative assessment prior to fielding. The Night Vision Lab instrumented test ranges for comparative assessment at Ft. A.P. Hill in Virginia and Grafenwoehr, Germany to measure diurnal cycles of atmospheric transmission in the long wave infrared (LWIR) spectral region, where First Generation thermal imagers operated.

The Night Vision Lab had specially designed transmissometers deployed at various ranges and locations at the two geographic locations to measure atmospheric transmission in different spectral bands. Diurnal cycle data was obtained over test periods lasting several weeks. The results substantiated and quantified the substantial improvement in atmospheric transmission in the LWIR compared to the visible and near infrared. The data also was used to update the standard atmospheric models for atmospheric absorption used at the time to predict transmission based on relative humidity, air temperature and visibility range. The model update was quite significant in terms of per cent atmospheric transmission (**CTE35)**. Additionally, the attenuation coefficients for scattering under the severe fog and haze conditions encountered were so different from the values in the models at that time, that the updates were called the Grafenwoehr-A.P. Hill (G/AP) model[41] and were implemented in the Air Force LOWTRAN atmospheric model **(CTE36)**.[42] It is interesting to note that during this same time period, atmospheric transmission under truly battlefield conditions was being performed at the Jefferson Proving Grounds (JPG) with tactical smoke obscurants. JPG was an Army test facility in Indiana which is one of the few test ranges in the developed world where battlefield smokes and live artillery fire could be

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[41] F. Shields, *NV&EOL G/AP Aerosol Atmospheric Model*, memo, September 7, 1978, available at <www.dtic.mil/dtic/tr/fulltext/u2/a107711.pdf>.

[42] F.X. Kneizy, E.P. Shettle, L.W. Abreu, J.H. Chetwynd, G.P. Anderson, *Users' Guide to LOWTRAN7* (Hanscom AFB, MA: Air Force Geophysics Laboratory, 16 August 1988), available at <www.dtic.mil/dtic/tr/fulltext/u2/a206773.pdf>.

deployed for testing. This Army laboratory research and development emphasizes the uniqueness of Army test facilities and their unique capabilities. This atmospheric measurement and predictive modeling research and development generate unique CTEs by the Service laboratories in support of Function 5.

Testbeds, Models and Techniques

In the development of any new technology that can provide leap ahead capabilities for the Warfighter, new facilities and test & evaluation (T&E) techniques are often needed for characterization of the performance of new equipment based on the new technology. This can be illustrated by the advent of I^2 and thermal imaging technologies for night fighting capability. I^2 and thermal imaging were first demonstrated in the early 1970s during Army combat operations in Vietnam. The Night Vision Laboratory, later NVESD, soon realized that there was a need for new definitions of performance metrics that related system parameters to combat missions such as navigation, reconnaissance, surveillance, target acquisition (RISTA) and fire control (FC). Additionally unique new test and evaluation facilities and procedures were required in order to quantify the performance of image intensifiers and thermal imagers, or FLIRs (Forward Looking Infrared), as well as new performance models to analyze and optimize performance for combat operations.

The Night Vision Lab set up a whole new in-house Division, called the Visionics Division (**CTE37)**, and recruited new scientists and engineers to define the new performance metrics and invent and develop the testbeds, techniques, and models to design and evaluate new systems based on I^2 and thermal imaging, referred to as electro-optics (EO, which includes visible sensors as well). New physics had to be discovered for the specification of the environmental atmospheric and target signatures that were representative of the stimuli and propagation in the new spectral regions being utilized. Whereas the desired performance was in terms of the ability of the sights to discern the environment in the infrared spectrum and discriminate enemy threats on the battlefield, new laboratory measurements and techniques had to be defined and designed that could quantify battlefield performance and be given to industry as specifications.

The basic system level performance metric was defined and established on the ability of electro-optical devices to resolve 4 bar patterns as a function of bar pattern frequency (**CTE38**) (how small was the spacing between the bars). This approach for defining a system performance metric was based on previous work by Otto Schade at Radio Corporation of America (RCA)[43] that had resulted in the well-known Air Force 3-bar pattern that always came on after late night television in the 1950s. John Johnson, the first Visionics Director, defined the EO system metric of bar pattern resolution in his seminal paper, *Analysis of Image Forming Systems* (**CTE39)**.[44] I^2 and thermal imaging performance models were developed based on this concept and validated against laboratory and field test results. Soldiers and civilians at the Night Vision Lab indicated detection, recognition and identification of images while looking through EO devices at tactical targets which emitted their infrared radiation through the local atmosphere to be gathered by the device optical system. Detection performance as a function of range to the target, target signature

[43] See "Otto H. Schade, Sr.," in *Memorial Tributes: National Academy of Engineering, Volume 2*, 252—273 (The Nationals Academies Press, 1984).
[44] J. Johnson, *Analysis of Image Forming Systems,* Proceedings at Image Intensifier Symposium, Fort Belvoir, VA, (October, 1958), 249-273.

and atmospheric condition was measured over an ensemble of observers. This data validated the analytic models[45] (**CTE40**) with quantified error bars for the prediction of the probability of an ensemble of observers to perform the task as a function of range and environmental conditions and target class.

In order to develop and model the performance of EO imagers, laboratory bench tests needed to be defined and implemented so that the imagers could be characterized without lengthy and expensive field experiments. The measurement of subjective resolution, or bar pattern resolution, for FLIR systems was defined as minimum resolvable temperature (MRT)[46] and the first bench testbed was fabricated in Visionics under an order from DARPA.[47] (**CTE41**). This MRT bench measurement was cloned for the other Service laboratories and industry. MRT became the standard characteristic figure of merit and production acceptance test for thermal imagers in DOD. However, since the critical component of an MRT evaluation was the human eye and there is a potentially large variation in eye acuity across the population, the Visionics test facility with its unique standard eyeball became the ultimate standard for FLIR evaluation against which all other facilities were calibrated. It also became the neutral adjudicator for the FLIR systems industry and community. This is a major example of a special purpose facility that provides a capability for the community that could not nor should be resident in any outside the government facility.

In addition to providing the modeling and subjective resolution measurements for the whole EO community, the Night Vision Lab's Visionics, along with other government laboratories, characterized the infrared environment for the rest of the community. Atmospheric propagation was characterized for many tactically significant battlefield conditions. Atmosphere parameters for degraded natural environments (fogs and hazes) in significant operational geographic locations (Central Europe) were measured and published for the community, for example incorporated in the LOWTRAN atmospheric model.[48] Infrared target signatures for tactically significant threat combat vehicles were measured and promulgated to the FLIR industry system designers and to the Army combat simulation community for sensor effectiveness on loss exchange ratio in combat simulations.

The Visionics technical area gave a large set of special purpose capabilities that could be used in the Army's development of weapons systems. It supplied new validated, analytic models to assess the performance of contractor proposals or threat sensors, adjudicate performance claims with scientific bench tests, indicate where technology could make performance objectives previously not attainable, show effects on RISTA due to threat countermeasures and countermeasures without costly field testing, indicate sensor performance degradation due to

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[45] J.A. Ratches, "Static performance model for thermal imaging systems" *Optical Engineering* 15, no. 6 (December 1976), 525—530; Richard H. Vollmerhausen and Eddie Jacobs, *The Targeting Task Performance (TTP) Metric: A New Model for Predicting Target Acquisition Performance*, Technical Report AMSEL-NV-TR-230, Revision 20 April 2004 (Fort Belvoir, VA: U.S. Army CERDEC, April 20, 2004 (revised)), available at <http://lib.semi.ac.cn:8080/tsh/dzzy/wsqk/SPIE/vol5076/5076-28.pdf>.

[46] R. Sendall and M. Lloyd, "Improved Specifications for Infrared Imaging Systems," *Proc. IRIS* 14, no.2 (1970), 109-129.

[47] J. Wood, "Laboratory Bench Analysis of Thermal Imaging Systems," *Optical Engineering* 13, no. 5 (1974), 93-197.

[48] F.X. Kneizy, E.P. Shettle, L.W. Abreu, J.H. Chetwynd, G.P. Anderson, Users' Guide to LOWTRAN7 (Hanscom AFB, MA: Air Force Geophysics Laboratory, August 16, 1988), available at <www.dtic.mil/dtic/tr/fulltext/u2/a206773.pdf>.

weather and tactics, and suggest new sensor system designs to industry. These models also were incorporated in Army large-scale battlefield simulations for assessing new technology and tactics.

This descriptive example for Army laboratories is not the only one. Similar activities in other Army laboratories were and are fulfilling the same government technology specification evaluation techniques for other technologies. Armor protection, electronic warfare, command and control, projectile lethality, missile guidance and control, vehicle mobility, human performance, and human performance limits are examples of other Army laboratory areas of expertise that work with industry and the user to measure and specify system performance.

Function 6: Respond to National Crisis

The role of the military in national emergencies in the homeland is normally to provide support to civilian and state agencies, not to conduct police operations.[49] There are exceptions for insurrection or defiance of qualified Federal orders. In rare cases the President can federalize state militias or even declare martial law. Emergencies include floods, hurricanes and tornadoes, earthquakes, large scale fires, and droughts. The usual case is when the local authorities request the assistance of the military, usually under the supervision of the state militia or National Guard. In the aftermath of Hurricane Katrina Federal authorities were asked for help and the Coast Guard and the U.S. Army took control of the rescue and recovery operations. The Corps of Engineers was involved in all aspects of the review and restoration of the levees in the New Orleans area. The Corps of Engineers and other Army units often help in providing clean water and temporary assistance with food and shelter.

The military laboratories are not usually involved directly in such emergencies. Their roles would have been either before or after the emergency. For example, research into improved medical treatment for burns and wounds is ongoing at the laboratories of the Army Medical Research and Materiel Command. Planners at the laboratories learn from disasters and tailor programs accordingly. After the disruption caused by the mailing of anthrax spores to public figures, new research resulted in new means of detection and response to chemical and biological attacks. This work produced new detectors and new models for predicting how air plumes carrying toxic agents would behave **(CTE42)**. In some cases the disaster serves to increase the pace and funding of existing programs at the laboratories.

In time of war the laboratories focus more sharply on solving immediate challenges facing warfighters. The use of IEDs by our antagonists in Iraq and Afghanistan led to many research programs, some under JIEDDO (Joint IED Defeat Organization). The IEDs were creating havoc for Army and Marine vehicles. Some IEDs were buried under roads; others were placed in culverts or hidden at the roadside. Army labs created some devices that were useful in jamming remote detonating devices **(CTE43)**. The Army's experts in armor devised, in short order, new up-armor systems that were added (bolted on) to vulnerable vehicles such as HMMWVs and Strykers **(CTE15)**.

[49] Charles Doyle and Jennifer K. Elsea, *The Posse Comitatus Act and Related Matters: The Use of the Military to Executive Civilian Law* (Washington, DC: Congressional Research Service, August 16, 2012).

The ARL fielded a system designed to detect and pinpoint trajectories of incoming artillery and mortar rounds. This fielding was funded by the Army's Rapid Equipping Force (REF). Called UTAMS for Unattended Transient Acoustic/Artillery MASINT Systems, the system was developed in the ARL as part of its acoustic sensors program **(CTE44)**. UTAMS can be set up as an unattended ground sensor system or mounted on surveillance aircraft (Aerostats). The system uses a set of microphones that integrates the signals and are used to triangulate positions.[50]

Transportation of fuel and water on the battlefield has become a major problem in Iraq and Afghanistan because of the costs and hazards in sending convoys across roads where IEDs and insurgent attacks occur all too often. Army technical experts responded to this problem by helping to introduce alternatives. The fuel needed for power generation can be partially replaced by use of wind or solar generators **(CTE45)**. Natick Soldier RDEC has developed the use of flexible solar cells applied to tentage, more insulation, and the use of LEDs in place of ordinary lighting **(CTE46).**[51] Generation of energy from waste by a combination of fermentation and gasification has been demonstrated in Iraq by RDECOM Edgewood Chemical and Biological Center (ECBC) **(CTE47)**.[52]

Sensor technology is a major capability resident in the Services' inventory as a result of their research and development investment and due to the threat that they face. However, sensor technology can have major benefits to non-military applications, especially during times of national crises, such as natural disasters. During the aftermath of Hurricane Katrina, the Compact Airborne Spectral Sensor (COMPASS) was used in aircraft to scan flooded regions in/around New Orleans for submerged vehicles and poisonous gaseous plumes. COMPASS is a developmental compact visible/SWIR (0.4 to 2.35 µm) hyperspectral imager developed by the Communications and Electronics Research, Development and Engineering Center (CERDEC) at NVESD. The system produces 256 simultaneous spectral bands with 256 cross-track pixels per swatch with swath widths dependent on aircraft speed, altitude, and amount of overlap desired with adjacent tracks. Originally designed for target discrimination in camouflaged environments, it was used as an airborne asset to detect the submerged trucks and potential contaminant gas plumes in the flood waters and the extent to which mixing was occurring. COMPASS was even used to search for wreckage from the Columbia Space Shuttle, which discovered small particle debris (~ square centimeters) from the air.[53]

Another military sensing application is perimeter defense in order to acquire threats at the perimeter of defensive lines, Forward Operating Bases, ports, and borders. Cerberus is a mobile security sensor tower that has an integrated multi-sensing suite and was developed by CERDEC NVESD.[54] It is designed to be air lifted or towed into position with an array of sensor modalities: uncooled IR, ground surveillance radar, acoustic sensors, laser rangefinder, day camera, chemical sensors and GPS. More than one Cerberus can be linked together in a network to cover extended ranges along perimeters. The relevance of this Army development to the US border

[50] Ratches, Chait, and Lyons, *Some Recent Sensor-Related Army Critical Technology Events*.
[51] Information provided by Bindu Nair, Senior Staff Member, NSRDEC, e-mail on September 29, 2010.
[52] James J. Valdes and Jerry Warner, *Tactical Garbage to Energy Refinery*, EWCBC-TR-713 (Aberdeen Proving Ground, MD: U.S. Army Research, Development and Engineering Command, October 2009), available at <www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA510944>.
[53] Charts submitted by Mike Jennings, Division Director, Special Projects Division, CERDEC NVESD, April 24, 2013.
[54] Ibid., April 23, 2013.

control mission and their national crisis is obvious. The Cerberus technology has been picked up by the U.S. Customs and Border Protection and systems have been deployed.[55]

Function 7: Constructive Advisor Based on Expertise

> "The purpose of this function is to provide independent advice to the Services' and DOD's management on the efficacy, status, timeliness, and progress of acquisition programs. No other function of the laboratories is more contentious, but the complexity of these programs requires an independent voice to ensure the best systems for our fighting forces at an affordable cost."[56]

This statement by the Commission's report is the truly contentious part of new systems acquisition. The Army laboratory must have the respect of the industry contenders for an acquisition program. The laboratory cannot be perceived as having a favorite candidate for a solicitation. Its rationale for supporting or denying a proposal must rest securely on technical reputation and Army benefit and the rationale must be defensible against counter technical arguments. The technical reputation is only built up with years of participation in the relevant technical community.

It is also incumbent on the Army laboratory to be able to react to new science and technology being proposed. Ad hoc and impromptu field exercises are not uncommon to sort out pro and con with respect to new technologies. It is important for the laboratory to have a fall back field test location that can be utilized to sort out technical issues.

There are a number of ways the Army S&T community acts as a constructive expert/advisor to the Executive Officer community[57]:

(a) Acting as the resident on-site SME with the PM in discussions with proposing contractors to help assess the voracity and viability of the approach under discussion.
(b) Estimating technology impact/utility and optimization with modeling and simulation trade-offs and lessons learned from previous acquisition programs.
c) Suggesting new approaches as new requirements evolve, e.g., small mini-sensors payloads for the evolving UAS and UAV requirements.
d) Performing trade studies versus the array of operational problems being addressed.
e) Suggesting trade-offs in the performance and SWAP-C space.
f) Ensuring daily collaboration so that timely technical inputs can be made.
g) Assessing training issues with the new technology and consideration of devices and procedures on how to train.
h) Consideration of alternative technologies that may be competitive to proposed solution.

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[55] "Border Patrol Radar-Camera System Detects Migrants," *The Associated Press*, January 20, 2009, available at <www.azcentral.com/news/articles/2009/01/20/20090120border-camera0120-ON.html>
[56] Adolph, *Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories*, C-2.
[57] Eric Zipperer, member of Project Executive Office: Soldier Office, interviewed by authors, March 8, 2013.

i) Consideration of counter and counter-countermeasures for proposed system concept.
j) Suggesting field solutions through the Field Assistance & Technology (FAST) program. These efforts are staffed by Army laboratory personnel on detail for specific time periods—a year or longer.

A good example of suggesting new approaches as new requirements evolve is the study conducted by Human Research and Engineering Directorate (HRED) of ARL. The study looked at the performance of one and two I^2 goggle tubes for land navigation. The land navigation perceptibility was analyzed compared to the weight penalty associated with the extra tube on the head.

A major example of a program that was terminated in the Army due to technical persistence on the part of an Army lab was the electric gun. The Weapons Material Research Directorate (WMRD) of ARL over several years challenged the development of an electric gun for ground combat vehicles based on technical rationale (size of system). After several years of research, the proponent could no longer contest the ARL arguments against the development of such a technology for combat vehicles. Nevertheless, the program was picked up by the U.S. Navy **(CTE48)**.

Function 8: Support the User in the Application of Emerging Technology and Introduction of New Systems

> "In executing this function, the laboratories rapidly insert technology advances into operational forces and assist the user in adapting technologically sophisticated equipment for the operational environment. In the process of doing this, the laboratories gain the knowledge to undertake Function Nine: Translate user needs into technology requirements for industry and to most effectively provide the central role of the smart buyer."[58]

The recent conflicts in Iraq and Afghanistan generated new combat threats to US forces. The most prolific and enduring was the use of IEDs, which were buried in or on the sides of roadways that provided a significant threat to US forces due to their pervasiveness, low profile, covertness, and lethality. Besides their lethality, IEDs were significant detriments to the operational tempo. The detection of buried IEDs in roads became a significant challenge to the Army R&D community. There were many suggested and tried solutions to the IED including metal detectors, disturbed earth detection, explosive effluent detection, change detection, and many more.

Arguably, the most successful approach to IED detection in roadways in Afghanistan was the use of ground penetrating radar (GPR) **(CTE49)**. The research on GPR was pursued for more than fifteen years previously. The inventor of the concept was Gunther Wichmann of the German Defense Ministry (Fraunhofer). Under a Defense Exchange Agreement (DEA) between the US (CERDEC NVESD) and Germany, the technology was developed by an NVESD contractor

[58] Adolph, *Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories*, C-2.

BRTRC, which spun off the company NIITEK for this application. The GPR systems were slated to go onto the Ground Stand-off Mine Detection System (GSTAMIDS) in 2000. The vehicle was to be the Huskey countermine vehicle. The main performance limitation was the effects of ground bounce of the radar signal return that bounced around the standard conical radar receiver generating a significant false alarm rate.

NVESD in collaboration with Dr. Wichmann came up with a non-standard, low radar cross section antenna design based on the bandwidth and system design determined by NVESD. Signal processing algorithms with automatic target recognition were incorporated and a functional system was demonstrated **(CTE50)**. The GPR sensor was integrated into a South African Huskey countermine vehicle that had been acquired under a Foreign Comparative Technology program award. The innovation associated with the selection of Huskey was that vehicle has been developed by the South Africans for countermine. The underbelly of the vehicle was V-shaped design to mitigate the blast of mine explosions. The Army laboratories had done their homework ahead of time and were ready for the threat when it occurred **(CTE51)**. The new vehicle with the blast resistance became the Mine Resistant Anti-Armor Protection (MRAP) system. Later versions on MRAP implemented rollers on the front of the vehicle in order to explode any devices **(CTE52)**.

There were many other approaches to IED detection and neutralization. A multispectral approach in a wand configuration fused metallic detection with GPR. Another multispectral approach detected changes in the emitted spectrum from disturbed versus undisturbed earth. Undisturbed earth has a relatively smooth spectrum in the region around nine micrometers. However, earth that has been disturbed in burying mines has much more spectral structure in this region and can be observed with a sensor sensitive in this region **(CTE53)**. Moreover, the signal strength due to the different particle distribution deteriorated over time as the earth returned to its undisturbed state. An ARL counter-IED system focused on the electronics in 155 mm and Explosively Formed Penetrators IEDs **(CTE54)** was fielded in 2006 in Iraq.

Finally, another IED detection process was the use of change detection (**CTE55)**. This approach was compatible with use of airborne imaging sensors from an airplane. An imaging sensor would be flown down a road before friendly forces used the road. Just before the force would pass down the road, a second flight would be made and any anomalous differences would indicate the potential for something being buried at that location. An investigative force would then be sent to interrogate before a convoy would pass down the road.

There is another activity that the laboratories perform that falls under this function. The laboratories generate and nurture the adoption by industry of new technologies. When there are no obvious commercial applications and, consequently non-military markets, for research in a new technical area, the labs must provide funding to industry to enable industrial involvement in those technologies that might/will be critical to new military capabilities. The government labs must not only fund their own research but must provide incentives and provide support to nascent industrial capabilities in those technologies until they are mature enough to carry the development to maturity for weapons platforms.

When the maturity is sufficient to enable new military capability, then the industrial base will aggressively pursue competitively roles in new weapons systems development that are enabled by the new technologies. The government labs define the new technologies and ensure the transition to the industrial base. “The Government labs defined technologies that had the promise

of making a difference for the Warfighter and provided seed funding and management of its development through the funding provided by DOD. Although there could be counter arguments that industry could provide those laboratory functions, it has proven in the past that most of their IR&D funds [projects under Independent Research and Development supported within DOD contracts for systems] are rarely successful without government guidance and would soon dry up if there were no government interest."[59]

An example of Army laboratories generating a technology for a whole new commercial industry is the development of gallium arsenide (GaAs) for electronics fostered by DARPA and laboratory staff at Fort Monmouth NJ. The unique Army investment in GaAs material in the 1980s led to devices for microwave integrated circuits (MMICs). MMICs enable the development of the cell phone industry. We remind the reader of the Army's role in the development and fielding of the ENIAC.

Function 9: Translate Needs to Industry

The Army laboratories perform the unique function of translating Army Warfighting requirements into technical system parameters that specify to industry what the system design must be to satisfy those requirements. Required performance with respect to lethality, protection, maneuver, sensing, navigation, command and control, communications, countermeasures and counter-countermeasures, mobility, etc. need technical characteristics that can be specified and then measured and optimized through established scientific measurements and field exercises. The Army Laboratories have the scientific knowledge and experience to translate the Warfighting capabilities into system reproducible measurements that can be quantified in the laboratory. The laboratory provides the requisite facilities and knowledge to conduct verifying experiments on candidate solutions from industry. Typically, the laboratory establishes the measurement techniques and bench tests to evaluate industry proposed solutions to the established requirements. These techniques and facilities become the canonical scientific approaches across industrial entities; they ensure fairness in competition and promote a universal path to optimal Army requirements satisfaction. The Army laboratories become the "neutral adjudicator" for the various industrial proposals to satisfy Army stated requirements by using the established scientific evaluation techniques, test facilities and validated analytic models that can extrapolate to analyze concepts with the established state-of-the-art techniques in the community when hardware is not available. Army scientists and engineers conduct workshops to understand the latest innovations in technology and to inform Warfighters as to the availability of technology suitable for their needs.

An effective way that the Army laboratories translate Army needs to industry is through verified, validated, and accredited (VV&A) analytical models for Army tactical systems. Models that relate system design parameters to performance on the battlefield enable the quantification of system parameters that can be documented and solicited by the Army to industry. Examples are: 1) models that use optical parameters and detector sensitivity to predict target detection ranges; 2) projectile size and charge to give target engagement ranges; 3) missile launch angle and burn time to give engagement ranges, and so on. Historically, Army models have been VV&A by the Army Material Systems Analysis Agency to ensure that the predictions correspond to reality within some acceptable performance bracket. Models from all the various Army R&D organizations have been tested and compared to experimental data obtained from controlled field

exercises **(CTE56)**. VV&A system performance models have and continue to be integrated in larger battlefield engagement models, such as Army's Carmonette battlefield model where battle outcome can be assessed.[59]

The development of thermal imagers can be used as an example to this generation of technical specifications from military need and of the critical role played by the Service laboratory. Army laboratories have quantified the tactical environment for combat engagements by measuring the distribution of target signatures (temperature difference between target and local background) in the spectral regions of interest for combat vehicles, helicopters, individual Soldiers, and backgrounds to represent the input signal for an IR sensor. When measured over sufficient data set, the distribution of the input signal can be quantified and the distribution of occurrences indicated. The atmospheric transmission can be established based on validated atmospheric propagation models given the relative humidity, air temperature and visibility. Finally, the system performance as a function of system design parameters can be predicted and compared to the tactical requirement using a model such as a Johnson model.[60] System parameters can be optimized by the system designer for the battlefield performance required and those system parameters become the target for industrial system target designs **(CTE57)**. The Army laboratories become the repository of the environmental effects on sensor performance and the depository of all documented lab and field performance that has been obtained from government testing. A major function of Army laboratories is to be the archival repository of all data, including proposed, bench tested, field tested, and fielded systems that have been proposed to satisfy specific Army requirements.

Function 10: Serve as S&T Training Ground

The Army S&T laboratory community is a revolving door for military and civilian partners. The technical depth resides in the laboratories and the military need resides in Soldiers. However, there is constant cross fertilization with the rotation of Warfighters through the laboratories and S&E's through the Program Offices. Soldiers spend a rotation period assigned to a laboratory where they begin to understand the technologies that are adapted for the field and used by the Soldier. S&Es spend a year or more in program offices getting a firsthand experience with the acquisition process. Important lessons are learned as far as what are the real constraints that the tactical environment presents and which can impact the development and fielding of new technology.

Army professional acquisition personnel in many cases start out as an S&E in an Army laboratory and then transition to a project management facility **(CTE58)**. Management shops in many instances are geographically located at the same place as an RDEC where the relevant basic and applied research is done for the systems. Many bench scientists who are involved in the applied research that generates a system concept are sufficiently interested in what they have done to transition with the system technology to the Project Management and Executive Office shop. In this case, no technical training is required and the engineer can focus on later steps in acquisition planning and accomplishment. The engineer also brings new insight with him to

[59] Charles M. Shrader, *History of Operations Research in the United States Army, Volume III: 1973—1995* (Washington, DC: U.S. Army, 2009), 283.
[60] J. Johnson, *Analysis of Image Forming Systems,* Proceedings at Image Intensifier Symposium, Fort Belvoir, VA, (October 1958), 249-273.

management and acquisition activities that he has because of his S&T experience. There are numerous examples of ideas for system implementation resulting from ideas generated by the transformed bench scientist. Especially relevant to this idea are the RDEC 6.3 engineers who transition to a management activity and suggest many innovative concepts in the later phases of acquisition base due to the in depth understanding they has of the technology.

Lieutenant Colonel Joe Makin is a prime example of the role S&T laboratories play producing Soldiers as system Program Managers. Colonel Mackin was sent to the Massachusetts Institute of Technology and received his Ph.D. in physics. Upon returning to field assignment, Makin spent about 4 years at NVESD where he was Military Deputy. He led the laboratory's participation in the Combat ID Advanced Concepts Technology Demonstration (ACTD) and the Laser Countermeasure System (LCMS), and was the NVESD representative to the FLIR special task force. During his assignment at NVESD he learned all the requisite science and technologies associated with night vision sensors and system concepts: I^2, first generation FLIR Common Modules, tank gun sights, helicopter pilotage, among others. After several years assigned to NVESD, he became PM FLIR for 4 years for the Army's Intelligence, Electronic Warfare and Sensors (IEWS) Program Executive Office. As Project Manager, he oversaw the procurement of FLIRs for the Army, known as the FLIR Horizontal Technology Integration demonstration (HTI). HTI was a new, unique approach for procuring all the FLIRs required by the Army across all the platforms, instead of through stovepipes for each weapons platform. This was the first time that the same technology was procured across all platforms jointly with potentially large cost savings. Mackin learned all the acquisition aspects of fielding night vision, including industrial production, basis of issue, etc. and was able to facilitate the fielding of thermal imaging across the Army efficiently and cost effectively.

V. Findings, Discussion and Concluding Remarks

Findings

We have shown that the Army Tech Base laboratories, taken as a whole, perform all of the functions defined by the Federal Commission on Consolidation and Conversion of Defense Research & Development Laboratories (referred to as the Commission in the remainder of this paper). The ARL, RDECs, the Engineering Research and Development Center of the Corps of Engineers, and the laboratories of the Medical Research and Materiel Command have accomplished CTEs over the years that fall under all the Commission's required functions for Service laboratories. Examples have been shown here that are not evenly distributed across all Army S&T entities or across all functions. There have been 58 CTEs recognized in this study contributed by the Army laboratories. The CTEs described are but a small sample of the total CTEs produced by the Army Laboratory systems. The distribution of CTEs across all the 10 functions is given here:

- Infuse the Art of Possible – 12
- Maintain the Tech Base – 12
- Avoid Tech Surprise/Innovate – 8
- Support Acquisition Process – 2
- Provide Special Facilities – 7
- Respond to National Crisis – 6
- Be a Technical Advisor – 1
- Support User w/Emerging Tech and Introduce New Systems – 7
- Translate Needs to Tech Requirements – 2
- Serve As S&T Training Ground – 1

The Army laboratories are also conducting R&D beyond that represented by the 10 Commission functions. What has been presented in this report is only a small selection of all the CTEs actually carried out; however, each Army laboratory individually does not, necessarily, execute all ten functions defined by the Commission. We have not tried to measure this exactly.. However, it is suspected that most labs each execute a high percentage, if not all, of the total number of functions. The focus on the ten functions emphasizes the importance of the laboratories' accomplishments to the Army's needs. The needs of the Army's warfighters are the motivation that drives the Army laboratories as do commercialization and profit motivate private industry's laboratories.

Discussion

This report has shown with significant supporting documentation the relevance of the Army laboratories to the Army development of weapons systems as defined by the Commission's functions definitions. The value of the S&T laboratories to the ability of the Army to wage its nation's wars is substantiated. Previous CTE-based publications referenced throughout this paper articulate the quality of the staff and managers, the relevance of the S&T programs pursued, the

integration with the larger scientific community and the ability to forecast the technology trends. These are the underlying qualities of the laboratories that efficiently and effectively support the Army's evolving combat requirements. It would be redundant to repeat the testimony from these previous DTPs.

Concluding Remarks

Previous CTNSP reports in the *Project Hindsight Revisited* series concentrated on Critical Technology Events accomplished under several technical areas or weapons platforms development. The emphasis was on CTEs. This report changes the emphasis to demonstrating the Commission's functions required for a Service laboratory with the discussion of CTEs as representative of the functions being accomplished. In past *Hindsight* reports, the more the number of CTEs shown, the better. In this paper, CTEs are evidence only that a function is being addressed and CTEs become illustrative examples of a function. Choice of the illustrative CTEs for a given laboratory function is more important in this report than the total number of CTEs indicative of the previous reports. However, in all reports, the CTEs are the raw data that supports the technical justification for any claim of technical relevance or quality and impact.

Given the discussion above and the findings indicated, it seems that CTEs and their evaluation should/could play an important role in evaluation of military S&T portfolios. There is strong evidence of this in the previously published CTE-based reports on the Abram, Apache, Stinger and Javelin, and Sensors. The CTEs have become a validated method for assessing the benefit of the investment in technology development.

Given the importance of CTEs in the justification and documentation that the Army laboratories are performing their S&T functions in support of the Warfighter, the characteristics that produce CTEs, as presented in our previous document, should be reiterated here to support their continuance[61]:

1. Foresight and incorporation of technical advances when ready.
2. Awareness of what others are developing or have in-hand for another problem that could help your system.
3. New understanding gained from new experimental data or validated modeling results.
4. Utilization of unique/national facilities and intellectual talent outside of the laboratory, Service or the Nation.
5. Design modifications during R&D programs that address particular identified shortcomings or vulnerabilities.
6. Effective/efficient/enhanced transitions along R&D and system development cycle.
7. Learning lessons from others.
8. Pursuing competing approaches.

[61] Lyons, Chait, and Long, *Critical Technology Events in the Development of Selected Army Weapons Systems*.

Appendix A

Acronyms

ACTD – Advanced Concepts Technology Demonstration

AMC – Army Materiel Command

AMRDEC – Army Missile Research, Development and Engineering Center

AMSAA – Army Material Systems Analysis Agency

AN/PVS – Army Night/Passive Vision Sensor

ARDEC – Armaments Research and Development Center

ARL – Army Research Laboratory

ASK – Armor Survivability Kit

ATEC – Army Test and Evaluation Command

ATK – company, a tank ammunition manufacturer

BAE – company, BAE Systems.

BRAC – Base Relocation and Closure

BRL – Ballistics Research Laboratory

CARC – Chemical Agent Resistant Camouflage Coatings

CAS – Combat Ammunition Systems

CC&D – Camouflaged, Concealed, and Deception

CERDEC – Communications & Electronics Research, Development and Engineering Center

CFD – computational fluid dynamics

C4ISR – Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance

CHPPM – Center for Health Promotion & Preventive Medicine

COE – Corps of Engineers

COMPASS – Compact Airborne Spectral Sensor

CRA – Collaborative Research Alliance

CS/CSS – Combat systems/Combat Service Support

CTE – Critical Technology Event

CTNSP – Center for Technology and National Security Policy (NDU)

DARPA – Defense Advanced Research Projects Agency

DDR&E – Director of Defense Research and Engineering

DEA – Data Exchange Agreement

DOD – Department of Defense

DOT&E – Defense Operational Test & Evaluation

DTP – Defense & Technology Paper

DYNA3D – Lawrence Livermore code for simulating 3D impact

ECBC – Edgewood Chemical and Biological Center

ECH – Enhanced Combat Helmet

EDVAC – Electronic Discrete Variable Automatic Computer

EFP – Explosively Formed Penetrator (IED)

E&M or **EM –** Electro-magnetic

ENIAC – Electronic Numerical Integrator and Computer

EO – electro-optics

ERA – Explosive reactive armor

ERDC – Engineering Research and Development Center (Corps of Engineers)

ESTCP – Environmental Security Technology Certification Program

FAST – Future Assault Shell Technology

FC – Fire Control

FCS – Future Combat System

FCT – Foreign Comparative Technology

FLIR – Forward Looking Infrared

FOB – Forward Operating Base

FPA – focal plane array

G/AP – Grafenwoehr-A. P. Hill atmospheric model

GCS – Ground Combat Systems

GCV – Ground Combat Vehicle

GDATP – General Dynamics Armament and Technical Products

GDLS – General Dynamics Land Systems

GPR – Ground Penetrating Radar

GPS – Global Positioning System

GSTAMIDS – Ground Stand-off Mine Detection System

HMMWV – High Mobility Multipurpose Wheeled Vehicle

HPC – High Performance Computing

HRED – Human Research & Engineering Directorate (ARL)

HTI – Horizontal Technology Integration

ICME – Integrated Computational Materials Engineering

IEDs – Improvised Explosive Devices

IEWS – Intelligence, Electronic Warfare and Sensors

IR – infrared (spectral region of E&M spectrum)

I^2 – Image Intensification

JIEDDO – Joint IED Defeat Office

JPG – Jefferson Proving Ground, Indiana.

JPO – Joint Program Office

LCMS – Laser Countermeasure System

LOWTRAN – atmospheric transmission model

LTV – LTV Steel

LWIR – Longwave infrared (8-12/14 micrometers of EM spectrum)

ManTech – manufacturing technology Congressional funding category

MAS – Maneuver Ammunition Systems

MATV – Military All-Terrain Vehicle

MCP – Micro-channel plate

MCT – Mercury cadmium telluride IR detector material

MEDE – Modeling in Extreme Dynamic Environments

MEMS – micro-electromechanical systems

MRAP – Mine Resistant Anti-Armor Protection

MRMC – Medical Research and Materiel Command

MRT(D) – Minimum Resolvable Temperature (Difference)

M&S – modeling and simulation

MSME – Multiscale Modeling –Electronic (CRA program)

NASA – National Areonotics and Space Administration

NATO – North Atlantic Treaty Organization

NDU – National Defense University

NGEN – Next Generation Enterprise Network

NIR – Near infrared (~ 0.6 to 0.8 micrometers of EM spectrum)

NSRDEC – Natick Soldier Research, Development & Engineering Center

NSWC – Naval Surface Weapons Center

NVG – Night vision goggles

NVL or NVESD – Night Vision Lab, or today, Night Vision & Electronic Sensors Directorate (CERDEC)

ONR – Office of Naval Research

OPTEMPO – Operational tempo

OSD – Office of the Secretary of Defense

PC – photocathode (for an image intensifier)

PM/PEO – Project Manager/Program Executive Officer

PNVS – Pilot's Night Vision Sensor (I^2 sensor for pilotage)

POR – Program of Record

PVP – Profile Verification Program

R&D – Research & development

REF – Rapid Equipping Force

RDEC – Research, Development and Engineering Center

RDECOM – Research, Development and Engineering Command (under AMC)

RDT&E – Research, Development, Test & Engineering

RISTA – Reconnaissance, Intelligence, Surveillance and Target Acquisition

RXD – Research and exploratory development

S&E's – scientists and engineers

S&T – Science & Technology

SEDD – Sensors & Electron Devices Directorate (ARL)

SERDP – Strategic Environmental Research and Development Program

SME – Subject Matter Expert

SOCOM – Special Operations Command

SPD – Special Programs Division (of NVESD)

SRD – Sensor Research & Development

SW – Soldier Weapons

SWAP-C – Size, Weight and Power – Cost

SWIR – shortwave infrared spectral region ~ 1-2 micrometeres

TARDEC – Tank Automotive Research, Development and Engineering Center

TBI – Traumatic Brain Injury

TCA – Temperature Cycling Anneal (IR FPA process)

T&E – Test and Evaluation

TMAS – Tank and Medium-caliber Armament Systems

TTCP – The Technical Cooperation Program (US, UK, Canada, Australia & New Zealand)

UAS – Unattended Sensor

UAV – Unmanned Air Vehicle

UB – underbelly

USAIC – U.S. Army Intelligence Center

USMC – United States Marine Corps

UTAMS – Unattended Transient Acoustic/Artillery MASINT System

VV&A – Validation, Verification, and Accreditation

WMRD – Weapons and Material Research Directorate (ARL)

Appendix B

CTE Sources

CTE	Gov't Lab	Combined University/industry/Lab
1 ENIAC First Electronic Computer		**X**
2 Machine code f/computer		**X**
3 Internally stored computer program		**X**
4 Computer applied to new problems	**X**	
5 First Gen I^2		**X**
6 Second Gen I^2		**X**
7 Third Gen I^2		**X**
8 I^2 for ground combat missions	**X**	
9 I^2 for airborne missions	**X**	
10 SiC high power conversion	**X**	
11 ManTech to reduce SiC cost		**X**
12 Microrobots		**X**
13 IED Defeat Armor		**X**
14 Explosive Reactive Armor	**X**	
15 UB survivability		**X**
16 Transparent Armor	**X**	
17 Helmet Pre-form assembly machine	**X**	
18 Envir. friendly resistant camo. coatings		**X**
19 Advanced gun accuracy	**X**	
20 CFD & structural dynamics models	**X**	
21 Small caliber lethality technology	**X**	
22 Projectile flight motion dynamics	**X**	
23 CRA modeling awards	**X**	
24 Bridging scales of material models		**X**
25 Bolt-on Armor plate protection	**X**	
26 Sensing incoming rounds	**X**	

27 Blast resistant Pentagon structure	**X**	
28 Control of bleeding	**X**	
29 Shock treatment	**X**	
30 Desert disease treatment	**X**	
31 TBI treatment	**X**	
32 Pain management	**X**	
33 I^2 & thermal pilotage	**X**	
34 Thermal cycling anneal process	**X**	
35 Atmospheric model update	**X**	
36 GAP fog & haze model	**X**	
37 Visionics special facilities	**X**	
38 Bar pattern recognition for EO	**X**	
39 Johnson criteria	**X**	
40 Observer performance model	**X**	
41 MRT measurement bench test	**X**	
42 Air plume models	**X**	
43 IED jamming	**X**	
44 UTAMS	**X**	
45 Solar & wind generators	**X**	
46 LED Lighting		**X**
47 Energy from waste	**X**	
48 ARL pans electric gun	**X**	
49 GPR for mine/IED detection		**X**
50 ATR for mine detection	**X**	
51 Underbelly blast protection		**X**
52 Rollers on vehicle for mines	**X**	
53 Disturbed earth detection		**X**
54 Target electronics in IEDs	**X**	
55 Change detection for IEDs	**X**	
56 VV&A performance models	**X**	
57 Battlefield performance design models	**X**	
58 S&E transition to PM/PEO	**X**	

Appendix C

Individuals Contacted

Berry	**Mark**	**ARL-SEDD**	**CSE**
Brill	**Greg**	**ARL-SEDD**	**CSE**
Geil*	**Bruce**	**ARL-SEDD**	**CSE**
Jennings	**Michael**	**CERDEC NVESD**	**CSE**
Makin	**Joseph**	**EO/IR Associates**	**GR**
Nair	**Bindu**	**NSRDEC**	**CSE**
Neitubicz	**Charlie**	**ARL-WMRD**	**GR**
Petito	**Fred**	**CERDEC NVESD**	**CSE**
Plostins	**Peter**	**ARL-WMRD**	**CSE**
Pollard	**John**	**CERDEC NVESD**	**GR**
Reed	**Harry**	**ARL-WMRD**	**GR**
Reed*	**Meredith**	**ARL-SEDD**	**CSE**
Sherbonndy	**Kelley**	**ARL-SEDD**	**CSE**
Zipperer	**Eric**	**PEO Soldier**	**Contractor**

***Reviewed contributed section of report**

Appendix D

Project Hindsight

This study is modeled in part on a 1969 report, Project Hindsight. In 1965, the Director of Defense Research and Engineering (DDR&E), Dr. Harold Brown, established a project to take a retrospective look at U.S. Department of Defense (DOD) investment in research and development (R&D), to evaluate the results, and to take stock of lessons learned. Brown's overarching objectives for the study were to identify management factors that were associated with the utilization of the results produced by the Defense Department science and technology (S&T) program and to devise a methodology to measure the return on investment.[62] He was motivated in part by the House of Representatives Committee on Defense Appropriations, which had questioned the efficiency of management and overall payoff for the part of Research, Development, Testing and Evaluation program that pertained to S&T.[63]

The study was conducted by ad hoc teams of military and civilian in-house personnel. Some 20 weapons systems were selected for review and a set of subcommittees was arranged, one for each system. The systems selected for review included air-to-surface, ballistic, and tactical missiles; a strategic transport aircraft; a howitzer; and an antitank projectile. Data were gathered by questionnaire and evaluated according to four criteria:[64]

1. The extent of dependence on recent advances in science or technology.
2. The proportion of any new technology that resulted from DOD financing of science or technology.
3. The management or environmental factors that appear to correlate with high utilization of S&T results.
4. A quantitative measure of the return on investment.

The project teams make the following finding with respect to these four criteria:[65]

1. Markedly improved weapons systems result from skillfully combining a considerable number of scientific and technological advances (Criterion 1).
2. More than 85 percent of the new science or technology utilized was the result of DOD-financed programs (Criterion 2).
3. The utilization factor appears insensitive to environmental or management science and technology centers (Criterion 3).

[62] Harold Brown, *Letter to the Assistant Secretary of the Army (R&D), the Assistant Secretary of the Navy (R&D), and the Assistant Secretary of the Air Force (R&D), July 6, 1965,* in, *Project "Hindsight: Final Report"* (Washington, DC: Department of Defense, 1969), 135.
[63] Ibid., 135.
[64] *Project "Hindsight: Final Report"*, xiii.
[65] Ibid., xxi.

4. Most utilized new technological information was generated in the process of solving problems identified in advanced or engineering development (Criterion 3).
5. Most utilized new fundamental scientific information came from organized research programs undertaken in response to recognized problems (Criterion 3).
6. Technological inventiveness and the utilization rate are dependent on the recognition of a need, an educated talent pool, capital resources, and an adequate communication path to potential users (Criterion 3).
7. Any crude approximation in measuring cost-performance will tend to be delusory (Criterion 4).

With regard to finding number seven, the study failed to find a satisfactory method for assessing cost benefit or cost performance from S&T work. To illustrate the difficulty that the study encountered, the report cited the example of the silicon-based integrated circuit. The circuit, invented during the period under review, revolutionized electronics and information technology and became a crucial part of virtually every system in the arsenal; there was no effective way to subdivide the effects on individual S&T programs.

This paper did not attempt to redress this or any other shortcoming of Project Hindsight; Dr. Brown's goal of quantifying the payoff of DOD investment in research and technology is if anything a loftier target today than it was in 1965. The fundamental purpose of this report, however, closely mirrors that of its predecessors: by examining the development of select Army systems, and in particular those signal technology events that propel systems to success, we hope to shed light on the factors that lead defense S&T research to fruition.

In addition to sharing a broad goal with the original Hindsight report, this paper also takes from it a similar unit of analysis, the CTE. Hindsight evaluations were based on a concept called a Research and Exploratory Development (RXD) Event. In that report, a RXD event has the predominant meaning of an event that "defines a scientific or engineering activity during a relatively brief period of time that includes the conception of a new idea and the initial demonstration of its feasibility."[66] There may be one or two such events in the development of a component or system, or a whole string of such events. In the case of basic research RXD events, the report distinguishes between undirected (i.e., curiosity-driven) and directed (i.e., problem-driven) work. Lastly, the final fabrication of the system component or device "may or may not involve an Event depending on the state of the technological art at the time of fabrication."[67] Please note that our signal events, CTEs, differ from Hindsight's RXD events. Most significantly, CTEs can occur at any point in the life cycle. We leave open the possibility that CTEs might result from efforts that have utilized funds other than R&D.

[66] *Project "Hindsight: Final Report"*, xiv.
[67] Ibid.